On hadron production in Pb–Pb collisions at 158A GeV

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A Fermi statistical model analysis of hadron abundances and spectra obtained in several relativistic heavy ion collision experiments is utilized to characterize a particle source. Properties consistent with a disintegrating, hadron evaporating, deconfined quark-gluon plasma phase fireball are obtained, with a baryochemical potential $\mu_B = 200$–$210\,\mathrm{MeV}$, and a temperature $T_f \simeq 140$–$150\,\mathrm{MeV}$, significantly below previous expectations.

Discovery and study of quark-gluon plasma (QGP), a state consisting of mobile, color charged quarks and gluons, is the objective of the relativistic heavy ion research program underway at Brookhaven National Laboratory, New York and at CERN, Geneva [1]. Thermalization of the constituents of the deconfined phase created in high energy large nuclei collisions is a well working hypothesis, as we shall see. The multi-particle production processes in 158A GeV Pb–Pb collisions carried out at CERN-SPS will be analyzed in this paper, using the principles of the statistical Fermi model [2]: strongly interacting particles are produced with a probability commensurate with the size of accessible phase space. Since the last comprehensive review of such analysis has appeared [3], the Pb-beam experimental results became available, and model improvements have occurred: we implement refinements in the phase space weights that allow a full characterization of the chemical non-equilibria with respect to strange and light quark flavor abundances [4,5]. Consideration of the light quark chemical non-equilibrium is necessary in order to arrive at a consistent interpretation of the experimental results of both the wide acceptance NA49-experiment [6–10] and central rapidity (multi)strange (anti)baryon WA97-experiment [11–13].

We further consider here the influence of collective matter flow on $m_\perp$-particle spectra and particle multiplicities obtained in a limited phase space domain. The different flow schemes have been described before [14]. We adopt a radial expansion model and consider the causally disconnected domains of the dense matter fireball to be synchronized by the instant of collision. We subsume that the particle (chemical) freeze-out occurs at the surface of the fireball, simultaneously in the CM frame, but not necessarily within a short instant of CM-time. Properties of the dense fireball as determined in this approach offer clear evidence that a QGP disintegrates at $T_f \simeq 144\,\mathrm{MeV}$, corresponding to energy density $\varepsilon = \mathcal{O}(0.5)$ GeV/fm^3 [15]. Our initial chemical non-equilibrium results without flow have been suggestive that this is the case [16], showing a reduction of the chemical freeze-out temperature from $T_f = 180\,\mathrm{MeV}$ [17]; an earlier analysis could not exclude yet higher hadron formation temperature of 270 MeV [18].

The here developed model offers a natural understanding of the systematic behavior of the $m_\perp$-slopes which differs from other interpretations. The near equality of (inverse) slopes of nearly all strange baryons and antibaryons arises here by means of the sudden hadronization at the surface of an exploding QGP fireball. In the hadron based microscopic simulations this behavior of $m_\perp$-slopes can also arise allowing for particle-dependent freeze-out times [19].

In the analysis of hadron spectra we employ methods developed in analysis of the lighter 200A GeV S–Au/W/Pb system [5], where the description of the phase space accessible to a hadronic particle in terms of the parameters we employ is given. Even though we use six parameters to characterize the hadron phase space at chemical freeze-out, there are only two truly unknown properties: the chemical freeze-out temperature T_f and light quark fugacity λ_q (or equivalently, the baryochemical potential $\mu_B = 3\,T_f \ln \lambda_q$) – we recall that the parameters γ_i, $i = q, s$ controls overall abundance of quark pairs, while λ_i controls the difference between quarks and antiquarks of given flavor. The four other parameters are not arbitrary, and we could have used their tacit and/or computed values:
1) the strange quark fugacity λ_s is usually fixed by the requirement that strangeness balances $\langle s - \bar{s}\rangle = 0$ [4]. The Coulomb distortion of the strange quark phase space plays an important role in the understanding of this constraint for Pb–Pb collisions, see Eq. (1) [16];
2) strange quark phase space occupancy γ_s can be computed within the established kinetic theory framework for strangeness production [20,21];
3) the tacitly assumed equilibrium phase space occupancy of light quarks $\gamma_q = 1$; and
4) assumed collective expansion to proceed at the relativistic sound velocity, $v_c = 1/\sqrt{3}$ [21].
However, the rich particle data basis allows us to find from experiment the actual values of these four parameters, allowing to confront the theoretical results and/or hypothesis with experiment.

The value of λ_s we obtain from the strangeness con-

servation condition $\langle s-\bar{s}\rangle = 0$ in QGP is, to a very good approximation [16]:

$$\tilde{\lambda}_s \equiv \lambda_s \lambda_{\rm Q}^{1/3} = 1\,, \qquad \lambda_{\rm Q} \equiv \frac{\int_{R_{\rm f}} d^3 r e^{\frac{V}{T}}}{\int_{R_{\rm f}} d^3 r}\,. \qquad (1)$$

$\lambda_{\rm Q} < 1$ expresses the Coulomb deformation of strange quark phase space. This effect is relevant in central Pb–Pb interactions, but not in S–Au/W/Pb reactions. $\lambda_{\rm Q}$ is not a fugacity that can be adjusted to satisfy a chemical condition, since consideration of $\lambda_i,\ i = u, d, s$ exhausts all available chemical balance conditions for the abundances of hadronic particles. The subscript R_f in Eq. (1) reminds us that the classically allowed region within the dense matter fireball is included in the integration over the level density. Choosing $R_{\rm f} = 8\,$fm, $T = 140\,$MeV, $m_s = 200\,$MeV (value of γ_s is practically irrelevant), for $Z_{\rm f} = 150$ the value is $\lambda_s = 1.10$.

In order to interpret particle abundances measured in a restricted phase space domain, we study abundance ratios involving what we call compatible hadrons: these are particles likely to be impacted in a similar fashion by the not well understood collective flow dynamics in the fireball. The available particle yields are listed in table I, top section from the experiment WA97 for $p_\perp > 0.7$ GeV within a narrow $\Delta y = 0.5$ central rapidity window. Further below are shown results from the large acceptance experiment NA49, extrapolated to full 4π phase space coverage. There are 15 experimental results. The total error $\chi^2_{\rm T} \equiv \sum_j (R^j_{\rm th} - R^j_{\rm exp})^2/(\Delta R^j_{\rm exp})^2$ for the four theoretical columns is shown at the bottom of table I along with the number of data points 'N', parameters 'p' used and (algebraic) redundancies 'r' connecting the experimental results. For $r \neq 0$ it is more appropriate to quote the total $\chi^2_{\rm T}$, with a initial qualitative statistical relevance condition $\chi^2_{\rm T}/(N-p) < 1$. The four theoretical columns refer to results with collective velocity v_c (subscript v) or without ($v_c = 0$). We consider data including 'All' data points, and also analyze data excluding from analysis four Ω, $\overline{\Omega}$ particle ratios, see columns marked 'No-Ω. Only in letter case we obtain a highly relevant data description. Thus to describe the Ω, $\overline{\Omega}$ yields we need an additional particle production mechanism beyond the statistical Fermi model. We noted the special role of these particles, despite bad statistics, already in the analysis of the S-induced reactions [5].

Considering results obtained with and without flow reveals that the presence of the parameter v_c already when dealing only with particle abundances improves our ability to describe the data. However, $m_\perp$ spectra offer another independent measure of the collective flow v_c: for a given pair of values T_f and $v_{\rm c}$ we evaluate the resulting $m_\perp$ particle spectrum and analyze it using the spectral shape and kinematic cuts employed by the experimental groups. To find the best values we consider just one 'mean' strange baryon experimental value $\bar{T}^{\rm Pb}_\perp = 260 \pm 10$, since within the error the high $m_\perp$ strange (anti)baryon inverse slopes are overlapping. Thus when considering v_c along with $\bar{T}_\perp$ we have one parameter and one data point more. Once we find best values of $T_{\rm f}$ and $v_{\rm c}$, we study again the inverse slopes of individual particle spectra. We obtain an acceptable agreement with the experimental $T^j_\perp$ as shown in left section of table II . For comparison, we have also considered in the same framework the S-induced reactions, and the right section of table II show a good agreement with the WA85 experimental data [25]. We used here as the 'mean' experimental slope data point $\bar{T}^{\rm S}_\perp = 235 \pm 10$. We can see that within a significantly smaller error bar, we obtained an accurate description of the $m^{\rm S}_\perp$-slope data. This analysis implies that the kinetic freeze-out, where elastic particle-particle collisions cease, cannot be occurring at a condition very different from the chemical freeze-out. However, one pion HBT analysis at $p_\perp < 0.5$ GeV suggests kinetic pion freeze-out at about $T_k \simeq 120$ MeV [26]. A possible explanation of why here considered $p_\perp > 0.7$ GeV particles are not subject to a greater spectral deformation after chemical freeze-out, is that they escape before the bulk of softer hadronic particles is formed.

The six statistical parameters describing the particle abundances are shown in the top section of table III, for both Pb- and S-induced reactions [5]. The errors shown are one standard deviation errors arising from the propagation of the experimental measurement error, but apply only when the theoretical model describes the data well, as is the case here, see the header of each column — note that for the S-induced reactions (see [5]) the number of redundancies is large since same data comprising different kinematic cuts is included in the analysis. We note the interesting result that within error the freeze-out temperature $T_{\rm f}$ seen in table III, is the same for both the S- and Pb-induced reactions. The collective velocity rises from $v^{\rm S}_c = 0.5c$ to $v^{\rm Pb}_c \simeq c/\sqrt{3} = 0.58$. We then show the light quark fugacity λ_q, and note $\mu^{\rm Pb}_B = 203 \pm 5 > \mu^{\rm S}_B = 178 \pm 5\,$MeV. As in S-induced reactions where $\lambda_s = 1$, now in Pb-induced reactions, a value $\lambda^{\rm Pb}_s \simeq 1.1$ characteristic for a source of freely movable strange quarks with balancing strangeness, *i.e.,* $\tilde{\lambda}_s = 1$ is obtained, see Eq. (1).

$\gamma_q > 1$ seen in table III implies that there is phase space over-abundance of light quarks, to which, *e.g.,* gluon fragmentation at QGP breakup *prior* to hadron formation contributes. γ_q assumes in our data analysis a value near to where pions could begin to condense [27], $\gamma_q = \gamma^c_q \equiv e^{m_\pi/2T_f}$. We found studying the ratio h^-/B separately from other experimental results that the value of $\gamma_q \simeq \gamma^c_q$ is fixed consistently and independently both, by the negative hadron (h^-), and the strange hadron yields. The unphysical range $\gamma_q > \gamma^c_q$ can arise, since up to this point we use only a first quantum (Bose/Fermi) correction. However, when Bose distribution for pions is implemented, which requires the constraint $\gamma_q \leq \gamma^c_q$, we obtain practically the same results, as shown in second column of table III. Here we allowed only 4 free param-

eters, *i.e.* we set $\gamma_q = \gamma_q^c$, and the strangeness conservation constraint fixes λ_s. We then show in table III the ratio γ_s/γ_q, which corresponds (approximately) to the parameter γ_s when $\gamma_q = 1$ had been assumed. We note that $\gamma_s^{\rm Pb} > 1$. This strangeness over-saturation effect could arise from the effect of gluon fragmentation combined with early chemical equilibration in QGP, $\gamma_s(t < t_f) \simeq 1$. The ensuing rapid expansion preserves this high strangeness yield, and thus we find the result $\gamma_s > 1$, as is shown in figure 33 in [21].

We show in the bottom section of table III the energy and entropy content per baryon, and specific anti-strangeness content, along with specific strangeness asymmetry of the hadronic particles emitted. The energy per baryon seen in the emitted hadrons is nearly equal to the available specific energy of the collision (8.6 GeV for Pb–Pb, 8.8–9 GeV for S–Au/W/Pb). This implies that the fraction of energy deposited in the central fireball must be nearly the same as the fraction of baryon number. The small reduction of the specific entropy in Pb–Pb compared to the lighter S–Au/W/Pb system maybe driven by the greater baryon stopping in the larger system, also seen in the smaller energy per baryon content. Both collision systems freeze out at energy per unit of entropy $E/S = 0.185$ GeV. There is a loose relation of this universality in the chemical freeze-out condition with the suggestion made recently that particle freeze-out occurs at a fixed energy per baryon for all physical systems [28], since the entropy content is related to particle multiplicity. The overall high specific entropy content we find agrees well with the entropy content evaluation made earlier [29] for the S–W case.

Inspecting figure 38 in [21] we see that the specific yield of strangeness we expect from the kinetic theory in QGP is at the level of 0.75 per baryon, in agreement with the results of present analysis shown in table III. This high strangeness yield leads to the enhancement of multi-strange (anti)baryons, which are viewed as important hadronic signals of QGP phenomena [30], and a series of recent experimental analysis has carefully demonstrated comparing p–A with A–A results that there is quite significant enhancement [13,31], as has also been noted before by the experiment NA35 [32].

The strangeness imbalance seen in the asymmetrical S–Au/W/Pb system (bottom of table III) could be a real effect arising from hadron phase space properties. However, this result also reminds us that though the statistical errors are very small, there could be a considerable systematic error due to presence of other contributing particle production mechanisms. Indeed, we do not offer here a consistent understanding of the Ω, $\overline{\Omega}$ yields which are higher than we can describe. We have explored additional microscopic mechanisms. Since the missing Ω, $\overline{\Omega}$ yields are proportional (13%) to the $\Xi, \overline{\Xi}$ yield, we have tested the hypothesis of string fragmentation contribution in the *final state*, which introduces just the needed 'shadow' of the $\Xi, \overline{\Xi}$ in the $\Omega, \overline{\Omega}$ abundances. While this works for Ω, $\overline{\Omega}$, we find that this mechanism is not compatible with the other particle abundances. We have also explored the possibility that unknown Ω^*, $\overline{\Omega^*}$ resonances contribute to the Ω, $\overline{\Omega}$ yield, but this hypothesis is ruled out since the missing yield is clearly baryon–antibaryon asymmetric. Thus though we reached here a very good understanding of other hadronic particle yields and spectra, the rarely produced but greatly enhanced Ω, $\overline{\Omega}$ must arise in a more complex hadronization pattern.

We have presented a comprehensive analysis of hadron abundances and $m_\perp$-spectra observed in Pb–Pb 158A GeV interactions within the statistical Fermi model with chemical non-equilibrium of strange and non-strange hadronic particles. The key results we obtained are: $\tilde\lambda_s = 1$ for S and Pb collisions; $\gamma_s^{\rm Pb} > 1$, $\gamma_q > 1$; $S/B \simeq 40$; $s/B \simeq 0.75$; all in a remarkable agreement with the properties of a deconfined QGP source hadronizing without chemical re-equilibration, and expanding not faster than the sound velocity of quark matter. The universality of the physical properties at chemical freeze-out for S- and Pb-induced reactions points to a common nature of the primordial source of hadronic particles in both systems. The difference in spectra between the two systems arises in our analysis from the difference in the collective surface explosion velocity, which for larger system is higher, having more time to develop. Among other interesting results which also verify the consistency of our approach we recall: good balancing of strangeness $\langle \bar s - s\rangle = 0$ in the Pb–Pb case; increase of the baryochemical potential as the collision system grows; energy per baryon near to the value expected if energy and baryon number deposition in the fireball are similar. We note that given the magnitude of γ_q and low chemical freeze-out temperature, most (75%) of all final state pions are directly produced, and not resonance decay products. Our results differ significantly from an earlier analysis regarding the temperature at which hadron formation occurs. Reduction to $T_f = 140$–$145\,$MeV becomes possible since we allow for the chemical non-equilibrium and collective flow, and only with these improvements in analysis our description acquires convincing statistical significance, which e.g. a hadronic gas scenario does not offer [33]. Because we consider flow effects, we can address the central rapidity data of the WA97 experiment at the required level of precision, showing the consistency in these results with the NA49 data discussed earlier [17].

In our opinion, the only consistent interpretation of the experimental results analyzed here is that hadronic particles seen at 158A GeV nuclear collisions at CERN-SPS are formed directly in hadronization of an exploding deconfined phase of hadronic matter, and that these particles do not undergo a chemical re-equilibration after they have been produced.

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TABLE I. WA97 (top) and NA49 (bottom) Pb–Pb 158A GeV particle ratios and our theoretical results, see text for explanation.

Ratios	Ref.	Exp.Data	All	All$\|_v$	No-Ω	No-$\Omega\|_v$
Ξ/Λ	[12]	0.099 ± 0.008	0.107	0.110	0.095	0.102
$\overline{\Xi}/\bar\Lambda$	[12]	0.203 ± 0.024	0.216	0.195	0.206	0.210
$\bar\Lambda/\Lambda$	[12]	0.124 ± 0.013	0.121	0.128	0.120	0.123
$\overline{\Xi}/\Xi$	[12]	0.255 ± 0.025	0.246	0.225	0.260	0.252
Ω/Ξ	[12]	0.192 ± 0.024	0.192	0.190	0.078*	0.077*
$\overline{\Omega}/\overline{\Xi}$	[11]	0.27 ± 0.06	0.40	0.40	0.17*	0.18*
$\overline{\Omega}/\Omega$	[12]	0.38 ± 0.10	0.51	0.47	0.57*	0.60*
$\frac{(\Omega+\overline{\Omega})}{(\Xi+\overline{\Xi})}$	[11]	0.20 ± 0.03	0.23	0.23	0.10*	0.10*
$\frac{(\Xi+\overline{\Xi})}{(\Lambda+\bar\Lambda)}$	[22]	0.13 ± 0.03	0.109	0.111	0.107	0.114
$K^0_{\rm s}/\phi$	[7]	11.9 ± 1.5	16.1	15.1	9.89	12.9
K^+/K^-	[8]	1.80± 0.10	1.62	1.56	1.76	1.87
$p/\bar p$	[6]	18.1 ±4.	16.7	15.3	17.3	17.4
$\bar\Lambda/\bar p$	[24]	3. ± 1.	0.65	1.29	2.68	2.02
$K^0_{\rm s}$/B	[23]	0.183 ± 0.027	0.242	0.281	0.194	0.201
h^-/B	[23]	1.83 ± 0.2	1.27	1.55	1.80	1.83
		$\chi^2_{\rm T}$	19	18	2.1	1.8
		$N;p;r$	15;5;4	16;6;4	11;5;2	12;6;2

TABLE II. Experimental and theoretical $m_\perp$ spectra inverse slopes $T_{\rm th}$. Left Pb–Pb results from experiment NA49 [10] for kaons and from experiment WA97 [13] for baryons; right S–W results from WA85 [25].

	$T_\perp^{\rm Pb}$ [MeV]	$T_{\rm th}^{\rm Pb}$ [MeV]	$T_\perp^{\rm S}$ [MeV]	$T_{\rm th}^{\rm S}$ [MeV]
$T^{\rm K^0}$	223 ± 13	241	219 ± 5	215
T^Λ	291 ± 18	280	233 ± 3	236
$T^{\overline{\Lambda}}$	280 ± 20	280	232 ± 7	236
T^Ξ	289 ± 12	298	244 ± 12	246
$T^{\overline{\Xi}}$	269 ± 22	298	238 ± 16	246

TABLE III. Top section: statistical parameters, and their $\chi^2_{\rm T}$, which best describe the experimental results for Pb–Pb data, and in last column for S–Au/W/Pb data presented in Ref. [5]. Bottom section: specific energy, entropy, anti-strangeness, net strangeness of the full hadron phase space characterized by these statistical parameters. In the middle column we fix λ_s by requirement of strangeness conservation and choose $\gamma_q=\gamma_q^c$, the pion condensation point.

	Pb–No-$\Omega\|_v$	Pb–No-$\Omega\|_v^*$	S–No-$\Omega\|_v$
$\chi^2_{\rm T}$; $N;p;r$	1.8; 12; 6; 2	4.2; 12; 4; 2	6.2; 16; 6; 6
T_f [MeV]	144 ± 2	145 ± 2	144 ± 2
v_c	0.58 ± 0.04	0.54 ± 0.025	0.49 ± 0.02
λ_q	1.60 ± 0.02	1.605 ± 0.025	1.51 ± 0.02
λ_s	1.10 ± 0.02	1.11*	1.00 ± 0.02
γ_q	1.7 ± 0.5	$\gamma_q^c=e^{m_\pi/2T_f}$	1.41 ± 0.08
γ_s/γ_q	0.86 ± 0.05	0.78 ± 0.05	0.69 ± 0.03
E_f/B	7.0 ± 0.5	7.4 ± 0.5	8.2 ± 0.5
S_f/B	38 ± 3	40 ± 3	44 ± 3
s_f/B	0.78 ± 0.04	0.70 ± 0.05	0.73 ± 0.05
$(\bar s_f-s_f)/B$	0.01 ± 0.01	0*	0.17 ± 0.02